

# Detecting Dark Matter using Centrifuging Techniques

S. Mitra

*saibalm@science.uva.nl*

Instituut voor Theoretische Fysica

Universiteit van Amsterdam

1018 XE Amsterdam

The Netherlands

R. Foot

*foot@physics.unimelb.edu.au*

School of Physics

Research Centre for High Energy Physics

The University of Melbourne

Victoria 3010 Australia

January 2003

## Abstract

A new and inexpensive technique for detecting self interacting dark matter in the form of small grains in bulk matter is proposed. Depending on the interactions with ordinary matter, dark matter grains in bulk matter may be isolated by using a centrifuge and using ordinary matter as a filter. The case of mirror matter interacting with ordinary matter via photon-mirror photon kinetic mixing provides a concrete example of this type of dark matter candidate.

It is known that a large fraction of the mass of the universe is in the form of dark matter. Most of this dark matter is believed to exist in the form of as of yet unknown elementary particles. Many different types of candidates have been proposed, such as weakly interacting massive particles (WIMPS), strongly interacting massive particles (SIMPS) and charged massive particles (CHAMPS). Despite many experimental searches all attempts to detect these particles have failed. For a review see[1].

Interestingly there is one possible dark matter candidate which has not yet been experimentally scrutinized. The idea is that dark matter particles may have strong enough self interactions such that they can condense into small grains, and also interact with ordinary matter, such that a grain can remain on the surface of the Earth. A specific candidate for this kind of dark matter is provided by theories respecting mirror symmetry, as we will now briefly explain.

Mirror symmetry appears broken by the interactions of the known elementary particles (because of their left-handed weak interactions). Nevertheless, mirror symmetry can exist if one introduces for every particle a corresponding mirror particle, of exactly the same mass as the ordinary particle [2, 3]. These mirror particles interact with each other in exactly the same way that the ordinary particles do. The mirror particles are not produced (significantly) in laboratory experiments just because they couple very weakly to the ordinary particles. In the modern language of gauge theories, the mirror particles are all singlets under the standard  $G \equiv SU(3) \otimes SU(2)_L \otimes U(1)_Y$  gauge interactions. Instead the mirror fermions interact with a set of mirror gauge particles, so that the gauge symmetry of the theory is doubled, i.e.  $G \otimes G$  (the ordinary particles are, of course, singlets under the mirror gauge symmetry)[3]. Mirror symmetry is conserved because the mirror fermions experience  $V + A$  (right-handed) mirror weak interactions and the ordinary fermions experience the usual  $V - A$  (left-handed) weak interactions. Ordinary and mirror particles interact with each other predominately by gravity (and possibly by new interactions as we will explain below). Clearly, mirror matter is an ideal candidate for the dark matter inferred to exist in the Universe because it is dark and stable[4]. It also appears to have the right properties to explain a number of other interesting puzzles. For a review, see Ref.[5].

While we know that ordinary and mirror matter do not interact with each other via any of the *known* non-gravitational forces, it is possible that new interactions exist which couple the two sectors together. In Ref.[3, 6], all such interactions consistent with gauge invariance, mirror symmetry and renormalizability were identified. Of most importance for this paper is the photon-mirror photon kinetic mixing interaction. In quantum field theory, photon-mirror photon kinetic mixing is described by the interaction

$$\mathcal{L} = \frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu}, \quad (1)$$

where  $F^{\mu\nu}$  ( $F'_{\mu\nu}$ ) is the field strength tensor for electromagnetism (mirror electromagnetism). This type of Lagrangian term is gauge invariant and renormalizable and can exist at tree level[3, 7] or may be induced radiatively in models without  $U(1)$  gauge symmetries (such as grand unified theories)[8, 9, 10]. One effect of ordinary photon-mirror photon kinetic mixing is to give the mirror charged particles a small electric charge[3, 8, 9]. That is, they couple to ordinary photons with electric charge  $\epsilon e$ . The most important experimental particle

physics implication of photon-mirror photon kinetic mixing is that it modifies the properties of orthopositronium[8]. The current experimental situation is summarized in Ref.[11], which shows that  $|\epsilon| \lesssim 10^{-6}$ , with some evidence for  $|\epsilon| \approx 10^{-6}$  from the 1990 vacuum cavity experiment[12].

Understanding the possible astrophysical implications of photon-mirror photon kinetic mixing has been the subject of a number of recent papers[13, 14, 15, 16]. The existence of photon-mirror photon kinetic mixing allows mirror matter to explain a number of puzzling observations, including the pioneer spacecraft anomaly[17, 15], anomalous meteorite events[18, 14] and the unexpectedly low number of small craters on the asteroid 433 Eros[19, 16]. In Ref.[16], it was shown that these explanations require  $|\epsilon| \gtrsim 10^{-9}$ . Thus, the most interesting parameter range for  $\epsilon$  suggested by observations is

$$10^{-9} \lesssim |\epsilon| \lesssim 10^{-6}. \quad (2)$$

One other, perhaps very important implication of photon-mirror photon kinetic mixing which we have yet to mention is that it can provide a force which opposes the effect of gravity, so that a mirror matter fragment can potentially remain on the Earth's surface. Whether this actually happens, depends on the strength of the photon-mirror photon kinetic mixing compared to the weight of the fragment. If the mirror fragment is embedded inside ordinary matter, then the mirror atoms will have an average electrostatic energy induced by the photon-mirror photon kinetic mixing. The fragment can experience a strong force when this energy changes rapidly as a function of its position, e.g. at the boundary between a low and high density medium. In the appendix we derive the following equation for the electrostatic force exerted on a stationary fragment at the boundary between two media compared to its weight:

$$\frac{|F_{\text{static}}|}{|F_{\text{gravity}}|} \sim |\epsilon| 10^{10} (\text{cm}/R) \quad (3)$$

Here,  $R$  is the size of the fragment. For positive  $\epsilon$ , the electrostatic force is (typically) directed from the high density medium toward the low density medium, while for negative  $\epsilon$  the electrostatic force has the opposite direction. According to the above equation, a mirror matter fragment of size  $R = 1$  cm could remain on the Earth's surface if  $\epsilon$  is positive and  $\epsilon \gtrsim 10^{-10}$ . [Of course, if it impacted with high velocity, it would be buried some distance below the surface, as we will discuss]. For  $\epsilon$  less than  $10^{-10}$  it would fall toward the center of the Earth. If  $\epsilon < 0$ , then the mirror matter fragment would necessarily move into the ground (because in this case the electrostatic force is then attractive between the low density air and high density ground). But, because the ground is of varying composition, a fragment would stop after becoming completely embedded within the ground. The limit for this to happen would be of the same order of magnitude, i.e.  $|\epsilon| \gtrsim 10^{-10}$ .

If dark matter exists in the form of small grains in the ground, then one may try to isolate it by centrifuging soil samples. Modern ultracentrifuges are capable of an acceleration of about  $10^6 g$ . In the case of mirror matter Eq. (3) shows that increasing the force of gravity by a factor of a million will remove mirror matter fragments greater than 100 microns in size for  $10^{-10} \lesssim |\epsilon| \lesssim 10^{-6}$ . The simplest technique to detect the presence of small grains of dark matter is

to first weigh a soil sample, then centrifuge it for some time<sup>1</sup>, and then weigh it again. If there were indeed mirror matter grains present, then these should have been removed, leading to a lowering of the weight. In practice the sensitivity of such tests is limited to about one part in  $10^6$  by weight (for a 100 gram sample). Still, nobody has ever done this type of experiment before. Such a sensitivity may well be enough to discover this type of dark matter, if it exists (especially if the sample to be tested is chosen appropriately, see the discussion below).

A more sensitive test may be performed by attempting to catch the escaping dark matter fragments in a backing around the inside of the centrifuge. The backing should preferably be of inhomogeneous composition to maximize the probability of catching fragments in it. By centrifuging many soil samples the backing may become enriched with dark matter fragments. A direct weight measurement of the backing could confirm this. Alternatively, a sample of the backing may be centrifuged and tested for a decrease in weight as described above. Such a technique could yield a sensitivity of about 1 part in  $10^7 - 10^8$  by weight. One might worry that the velocity of the fragments could be too large to be caught in the backing, however it turns out that the frictional force of a mirror fragment moving in ordinary matter is quite large, as we also show in the appendix. The conclusion is that a mirror fragment (with initial velocity  $U_i$ ) will slow down enough to enable it to be captured in ordinary matter (of mass density  $\rho$ ) after a distance of order:

$$\begin{aligned} L &\sim \frac{10^{-7}}{\Lambda} \left( \frac{U_i}{300 \text{ m/s}} \right) \left( \frac{4 \text{ g/cm}^3}{\rho} \right) \text{ meters, for } U_i \lesssim 300 \text{ m/s} \\ L &\sim 10^{-7} \left( \frac{U_i}{300 \text{ m/s}} \right)^4 \left( \frac{10^{-8}}{\epsilon} \right)^2 \left( \frac{4 \text{ g/cm}^3}{\rho} \right) \text{ meters, for } U_i \gtrsim 300 \text{ m/s} \end{aligned} \quad (4)$$

where  $\Lambda = (|\epsilon|/10^{-8})^2$  for  $|\epsilon| \lesssim 10^{-8}$  and  $\Lambda = 1$  for  $|\epsilon| \gtrsim 10^{-8}$ . Since the speed at which a fragment will leave the centrifuge is less than about 1000 m/s, the above equation suggests that a backing thickness greater than about a millimetre will be adequate to capture small fragments.

Besides weight measurements, there could be other ways to detect small dark matter grains escaping from a centrifuge. Since the interaction between the dark matter particles and ordinary atoms are strong enough to keep small grains from sinking into the Earth, these interactions may also be strong enough to cause a dark matter grain to thermalize with its environment on not too long time scales. The escaping dark matter grains may thus also be detected using cryogenic calorimeters.

The next issue is what type of sample to use. If this type of dark matter were present during the Earth's formation it would be expected to be most abundant in the Earth's core. However, such dark matter may also be extraterrestrial in origin, for example it may come from small mirror matter space bodies if they collide with the Earth. In this case, this dark matter may be present on (or near)

---

<sup>1</sup>The centrifugation time required can be estimated from  $F_{\text{friction}}$ , Eq.(19), derived in the appendix. The velocity of the fragment, relative to the spinning test tube in a centrifuge, can be found by equating  $F_{\text{friction}} \approx F_{\text{acceleration}} \sim 10^6 g$ . From Eq.(19), this suggests  $U \gtrsim 0.2$  cm/s. Taking into account possible uncertainties in our approximations, a centrifugation time of 10 minutes should be adequate.

the Earth's surface; enhanced at various 'impact sites'. Various candidate sites have been discussed in Ref.[14], including Tunguska and a small yet specific site in Jordan. Furthermore, according to Eq.(4) the mirror matter fragments will be very close (centimeters!) to the surface (since the impact velocity in both of these events is expected to be less than 1 km/s because of atmospheric effects). More generally, it has been known for a long time that deep sea sediment is one place where extraterrestrial material accumulates significantly. It should also be a good place to test for the existence of mirror matter-type dark matter.

In conclusion, we have explored the possibility that dark matter may potentially exist on (or near) the Earth's surface. A specific example of such dark matter is provided by mirror matter with photon-mirror photon kinetic mixing interaction. This type of dark matter has yet to be experimentally tested. We have therefore proposed a new and inexpensive technique to directly test samples for the presence of this type of dark matter. In the case of mirror matter, we have shown that this test is effective for mirror matter fragments larger than 100 microns in the range of  $10^{-10} \lesssim |\epsilon| \lesssim 10^{-6}$ , with a sensitivity of up to 1 part in  $10^8$ .

## Acknowledgments

R.F. would like to thank Peter Haines for some valuable discussions.

## Appendix: Can a Mirror Matter Fragment Remain at the Earth's Surface?

In this appendix we will estimate the force on a mirror matter fragment embedded in an ordinary matter medium which is due to the photon-mirror photon interaction. We will call this force  $F^\epsilon$ . In general, for a fragment in motion (with velocity  $U$ ),  $F^\epsilon$  will contain a velocity dependent frictional term as well as a static term, that is

$$F^\epsilon = F_{\text{static}} + F_{\text{friction}} \quad (5)$$

where  $F_{\text{static}}$  is independent of  $U$  and  $F_{\text{friction}} \rightarrow 0$  as  $U \rightarrow 0$ . We will first estimate  $F_{\text{static}}$  and then consider  $F_{\text{friction}}$ .

Consider a mirror matter fragment with mass density  $\rho'$ , composed of mirror atoms of mass  $M_{A'}$ , embedded within ordinary matter. Suppose this fragment is at the interface of two homogeneous (ordinary matter) mediums, which we label medium 1 and medium 2 (e.g. air/earth or earth/quartz etc). Let  $A$  be the cross sectional area of the fragment measured parallel to the interface. If the fragment moves a distance  $dr$  orthogonal to the interface, then the number of mirror atoms moving from medium 1 to medium 2 is simply  $A\rho'dr/M_{A'}$  and the electrostatic potential energy of the fragment will change by an amount  $dE$ :

$$dE = (\langle\zeta_2\rangle - \langle\zeta_1\rangle) \frac{A\rho'dr}{M_{A'}} \quad (6)$$

where  $\langle\zeta_1\rangle$  ( $\langle\zeta_2\rangle$ ) are the mean electrostatic energies coming from the interactions of mirror atoms with the ordinary atoms of medium 1 (medium 2). Therefore it will experience an electrostatic force of:

$$F_{\text{static}} = (\langle\zeta_1\rangle - \langle\zeta_2\rangle) \frac{A\rho'}{M_{A'}} \hat{n} \quad (7)$$

Here  $\hat{n}$  is the unit normal vector of the interface, pointing from medium 1 to 2.

The energies  $\zeta_{1,2}$  are very small because they are suppressed by  $|\epsilon| \lesssim 10^{-6}$  and are most significant when the mirror and ordinary nuclei are close enough so that the screening effects of the electrons can be approximately ignored. If  $z$  is the distance between the mirror nuclei and the nearest ordinary nuclei, then

$$\begin{aligned}\zeta(z) &\simeq \frac{ZZ'\epsilon^2\epsilon}{z} & \text{for } z \lesssim r_2 \\ \zeta(z) &\simeq 0 & \text{for } z \gtrsim r_2\end{aligned}\tag{8}$$

where  $Z$  is the atomic number of the ordinary atoms,  $Z'$  is the (mirror) atomic number of the mirror atoms. The distance  $r_2$  is the radius over which significant electrostatic interaction occurs, which we will approximate to the second Bohr radius, i.e.

$$r_2 \approx 4a_0/Z' \sim 10^{-9} \text{ cm},\tag{9}$$

where  $a_0$  is the hydrogen Bohr radius.

Because of rapid thermal motion and the (typically) different chemical composition and structure of the mirror matter fragment and ordinary matter medium, to a good approximation, the mean value of  $\zeta_i$ ,  $\langle\zeta_i\rangle$ , is simply the value of  $\zeta(z)$  averaged over the volume occupied by atoms, that is:

$$\begin{aligned}\langle\zeta\rangle &\approx \frac{1}{\frac{4}{3}\pi a^3} \int_0^a \zeta(z) dV \\ &\approx \frac{1}{\frac{4}{3}\pi a^3} \int_0^{r_2} \frac{ZZ'e^2\epsilon}{r} 4\pi r^2 dr\end{aligned}\tag{10}$$

where  $a$  is the mean distance between atoms (typically about  $3 \times 10^{-8}$  cm for a solid).

Thus, for a solid, we estimate that

$$\begin{aligned}\langle\zeta\rangle &\approx \frac{3}{2}ZZ'e^2\epsilon\frac{r_2^2}{a^3} \\ &\approx \epsilon\left(\frac{Z}{Z'}\right)10^2 \text{ eV}\end{aligned}\tag{11}$$

Recall that the force due to the electrostatic interactions depends on the difference in  $\langle\zeta\rangle$  between the two mediums [Eq.(7)]. This will be medium dependent, depending on the chemical composition and structure of the mediums. But, from Eq.(11), it is clear that the difference in  $\zeta$  between two mediums will have the form:

$$\langle\zeta_1\rangle - \langle\zeta_2\rangle = \epsilon\lambda_{1,2}10^2 \text{ eV}\tag{12}$$

where  $\lambda_{1,2}$  is the ‘medium dependent’ part, which is a number of order 1. In going from a low density medium (such as air) to a high density medium, solid earth,  $\lambda_{1,2}$  is negative, which implies an attractive force if  $\epsilon$  is negative and a repulsive force if  $\epsilon$  is positive.

The force on the mirror fragment due to the electrostatic interactions can

be obtained by combining equations , Eq.(7) and Eq.(12) <sup>2</sup>,

$$\begin{aligned} F_{\text{static}} &= \frac{(\langle \zeta_1 \rangle - \langle \zeta_2 \rangle) \rho' R^2}{M_{A'}} \hat{n} \\ &= \epsilon \lambda_{1,2} 10^{13} (\rho' / (\text{g/cm}^3)) (R/\text{cm})^2 \hat{n} \text{ g cm/s}^2 \end{aligned} \quad (13)$$

where we have taken  $M_{A'} \sim 20M_{\text{proton}}$ ,  $A \sim R^2$  where  $R$  is the size of the object.

To find out if a mirror matter grain can remain at the Earth's surface, we have to compare this with the gravitational force  $F_{\text{gravity}}$ . With our notation,

$$|F_{\text{gravity}}| \sim \rho' R^3 g. \quad (14)$$

Hence,

$$\frac{|F_{\text{static}}|}{|F_{\text{gravity}}|} \sim |\epsilon| 10^{10} (\text{cm}/R) \quad (15)$$

where we have used that  $|\lambda_{1,2}| \sim 1$

Recall that  $F_{\text{static}}$  is the force on a mirror matter fragment embedded in an ordinary matter medium, where the fragment was at rest relative to the medium. As discussed in Eq.(5), for a fragment moving with relative velocity  $U$  there will be a velocity dependent frictional term,  $F_{\text{friction}}$  as well. Our purpose now is to estimate  $F_{\text{friction}}$ . The frictional effect of mirror matter moving through an ordinary matter medium has been considered previously in Ref.[14, 16], but in that case only the high velocity regime was examined ( $U \gg 1 \text{ km/s}$ ). For the purposes of this paper, we are particularly interested in the case where  $U \lesssim 1 \text{ km/s}$ , which hasn't been evaluated previously.

A mirror matter fragment moving through a homogeneous ordinary matter medium will experience a friction force caused by momentum transfer from collisions of mirror atoms with the ordinary atoms in the medium. If  $U \lesssim v_{\text{thermal}}$  then the frequency of collisions suffered by a mirror atom is roughly  $nv_{\text{thermal}}\sigma$ , with  $n = \rho/M_A \sim 10^{23}/\text{cm}^3$  is the number density of atoms in the ordinary medium,  $v_{\text{thermal}} \sim \sqrt{6k_b T_{\text{room}}/m_{\text{atom}}}$  is the average relative speed of mirror atoms relative to the ordinary atoms, both assumed to be of mass  $m_{\text{atom}}$ , and  $\sigma$  is the elastic cross section. In the Born approximation, the differential cross section is given by[20]

$$\frac{d\sigma}{d\Omega} = \frac{4M_A^2 \epsilon^2 e^4 Z^2 Z'^2}{(4M_A^2 U^2 \sin^2 \frac{\theta_{\text{scatt}}}{2} + \frac{1}{r_2^2})^2}. \quad (16)$$

This is just the Rutherford formula cutoff at a distance  $r_2$ , [Eq.(9)], which is the range of the potential. At low velocities,  $U \lesssim 300 \text{ m/s}$ , the second term in the denominator dominates over the first term and the cross section becomes approximately isotropic, and Eq.(16) reduces to

$$\sigma = 16\pi M_A^2 \epsilon^2 e^4 Z^2 Z'^2 r_2^4. \quad (17)$$

Observe that for  $|\epsilon| \gtrsim 10^{-8}$ ,  $\sigma \gtrsim r_2^2$  which is unphysical. In fact, the interaction has become so strong that the Born approximation breaks down. For  $|\epsilon| \gtrsim 10^{-8}$ ,

---

<sup>2</sup>Unless otherwise stated, we use natural units with  $\hbar = c = 1$ .

the cross section saturates at  $\sigma \sim r_2^2$ . Thus, we have:

$$\begin{aligned}\sigma &\sim 10^{-2}\epsilon^2 \text{ cm}^2 \text{ for } |\epsilon| \lesssim 10^{-8}, \\ \sigma &\sim 10^{-18} \text{ cm}^2 \text{ for } |\epsilon| \gtrsim 10^{-8}.\end{aligned}\tag{18}$$

Note that the above cross section is only valid provided that  $U \lesssim 300$  m/s. For larger velocities the cross section is suppressed by the first term in the denominator of Eq.(16), see Ref.[14, 16] for more discussion about the high velocity regime.

In a collision part of the relative momentum will be transferred. If the whole mirror matter fragment is moving with velocity  $U$  relative to the medium, the momentum transferred by the collisions will average out to about  $m_{\text{atom}}U$  per mirror atom per collision<sup>3</sup>. Therefore the friction force  $F_{\text{friction}}$  exerted on the fragment of mass  $M$  (taking  $m_{\text{atom}} \sim 20M_{\text{proton}}$ ) is approximately:

$$F_{\text{friction}} \sim M \sqrt{\frac{6k_b T_{\text{room}}}{m_{\text{atom}}}} n \sigma U \sim 10^9 \Lambda (M/\text{g}) (U/(\text{m/s})) \left( \frac{\rho}{\text{g/cm}^3} \right) \text{ g m/s}^2\tag{19}$$

where  $\Lambda = (|\epsilon|/10^{-8})^2$  for  $|\epsilon| \lesssim 10^{-8}$  and  $\Lambda = 1$  for  $|\epsilon| \gtrsim 10^{-8}$ .

From Eq.(19) we find that a mirror fragment with initial velocity  $U_i$  will slow down enough to enable it to be captured in ordinary matter after a distance of order:

$$L \sim \frac{10^{-7}}{\Lambda} \left( \frac{U_i}{300 \text{ m/s}} \right) \left( \frac{4 \text{ g/cm}^3}{\rho} \right) \text{ meters}\tag{20}$$

Recall that the above equation is roughly valid for  $U_i \lesssim 300$  m/s. For completeness, let us mention that in the case of  $U_i \gtrsim 300$  m/s, the corresponding distance is[14, 16]:

$$L \sim \frac{U_i^4 M_A^2 M_A}{160\pi\rho Z^2 Z'^2 \epsilon^2 e^4} \sim 10^{-7} \left( \frac{U_i}{300 \text{ m/s}} \right)^4 \left( \frac{10^{-8}}{\epsilon} \right)^2 \left( \frac{4 \text{ g/cm}^3}{\rho} \right) \text{ meters}.\tag{21}$$

Anyway, the net effect is that for low velocities,  $U \lesssim 1$  km/s we see from Eq.(20,21) that mirror matter fragments rapidly slow down in ordinary matter.

## References

- [1] M. L. Perl *et al.*, Int. J. Mod. Phys. A16, 2137-2164 (2001) [hep-ex/0102033].
- [2] T. D. Lee and C. N. Yang, Phys. Rev. 104, 256 (1956); I. Kobzarev, L. Okun and I. Pomeranchuk, Sov. J. Nucl. Phys. 3, 837 (1966); M. Pavsic, Int. J. Theor. Phys. 9, 229 (1974).

---

<sup>3</sup>Note that this implicitly assumes that the ordinary matter medium is in the solid state. For a gaseous ordinary matter medium such as air, air molecules would build up within the body and move along with it, which would effectively reduce the size of the frictional force compared to a solid (even taking account of the density difference). For a gaseous medium it is better to work in the rest frame of the mirror body, and examine the momentum transferred by the impacting air molecules (as was done in Ref.[14]).



- [3] R. Foot, H. Lew and R. R. Volkas, Phys. Lett. B272, 67 (1991).
- [4] S. I. Blinnikov and M. Yu. Khlopov, Sov. J. Nucl. Phys. 36, 472 (1982); Sov. Astron. 27, 371 (1983); E. W. Kolb, M. Seckel and M. S. Turner, Nature 514, 415 (1985); M. Yu. Khlopov *et al.*, Soviet Astronomy, 35, 21 (1991); M. Hodges, Phys. Rev. D47, 456 (1993); Z. Berezhiani, A. Dolgov and R. Mohapatra, Phys. Lett. B375, 26 (1996) [hep-ph/9511221]; N. F. Bell and R. R. Volkas, Phys. Rev. D59, 107301 (1999) [astro-ph/9812301]; S. Blinnikov, Surveys High Energy Physics, 15, 37 (2000) [astro-ph/9911138]; Z. K. Silagadze, Phys. At. Nucl. 60, 272 (1997) [hep-ph/9503481]; S. Blinnikov, astro-ph/9801015; R. Foot, Phys. Lett. B452, 83 (1999) [astro-ph/9902065]; Phys. Lett. B471, 191 (1999) [astro-ph/9908276]; R. Foot, A. Yu. Ignatiev and R. R. Volkas, Astropart. Phys. 17, 195 (2002) [astro-ph/0010502]; V. Berezhinsky and A. Vilenkin, Phys. Rev. D62, 083512 (2000) [hep-ph/9908257]; Z. Berezhiani, D. Comelli and F. L. Villante, Phys. Lett. B503, 362 (2001) [hep-ph/0008105].
- [5] R. Foot, hep-ph/0207175; R. Foot, Acta Phys. Polon. B32, 2253 (2001) [astro-ph/0102294]; A. Yu. Ignatiev and R. Volkas, Talk given at the Australian Institute of Physics Congress, July (2002); Z. Silagadze, Acta Phys. Polon. B32, 99 (2001) [hep-ph/0002255]; R. Foot, *Shadowlands: Quest for Mirror Matter in the Universe*, Universal Publishers, 2002.
- [6] R. Foot, H. Lew and R. R. Volkas, Mod. Phys. Lett. A7, 2567 (1992).
- [7] R. Foot and X-G. He, Phys. Lett. B267, 509 (1991).
- [8] S. L. Glashow, Phys. Lett. B167, 35 (1986).
- [9] B. Holdom, Phys. Lett. B166, 196 (1986).
- [10] M. Collie and R. Foot, Phys. Lett. B432, 134 (1998) [hep-ph/9803261].
- [11] R. Foot and S. N. Gninenko, Phys. Lett. B480, 171 (2000) [hep-ph/0003278].
- [12] J. S. Nico, D. W. Gidley, A. Rich and P. W. Zitzewitz, Phys. Rev. Lett. 65, 1344 (1990).
- [13] R. Foot, A. Yu. Ignatiev and R. R. Volkas, Phys. Lett. B505, 355 (2001) [astro-ph/0011156].
- [14] R. Foot, Acta Phys. Polon. B32, 3133 (2001) [hep-ph/0107132]; R. Foot and T. L. Yoon, Acta. Phys. Polon. B33, 1979 (2002) [astro-ph/0203152].
- [15] R. Foot and R. Volkas, Phys. Lett. B517, 13 (2001) [hep-ph/0108051].
- [16] R. Foot and S. Mitra, astro-ph/0211067
- [17] J. D. Anderson *et al.*, Phys. Rev. D65, 082004 (2002) [gr-qc/0104064].
- [18] J. A. Docobo, R. E. Spalding, Z. Cepelcha, F. Diaz-Fierros, V. Tamazian and Y. Onda, Meteoritics & Planetary Science 33, 57 (1998); <http://www.jas.org.jo/mett.html>; N. V. Vasilyev, Planet. Space Sci. 46, 129 (1998).

- [19] A. F. Cheng *et al.*, Science 292, 484 (2001).
- [20] See for example, E. Merzbacher, Quantum Mechanics (Second Edition)  
Wiley 1970, p 230.